

INTEGRATED OPTICAL DEVICES AND METHOD OF FABRICATION
THEREOF

FIELD OF THE INVENTION

[0001] This invention relates generally to integrated optical devices and a method of fabrication thereof.

BACKGROUND OF THE INVENTION

[0002] In telecommunication networks, a solution for bandwidth expansion has been the adoption of wavelength division multiplexing (WDM), which entails the aggregation of many different information-carrying light streams on the same optical fiber. A WDM system that is configured for dividing and combining four or more wavelengths (or channels) that are closely spaced (800 gigahertz or less) is called dense wavelength division multiplexing (DWDM). Integrated optical devices are fundamentally required in these systems. Recently, integrated optical devices having ring resonators coupled to linear waveguides have been developed for use in these systems. One such device is disclosed by U.S. Patent No. 6,608,947. This patent discloses a method of fabricating an optical device

having one or more ring resonators optically coupled to linear waveguides. High index dielectric or semiconductor material is used to form the ring resonators and the linear waveguides. This method involves numerous, processing steps, which include deposition, patterning using photolithography, and etching.

[0003] There is also a rise in the use of optical polymers and organic materials for producing optical components. U.S. Patent No. 5,764,820 discloses a method of forming an integrated electro-optical device having a polymeric waveguide structure. The polymeric materials to be used for the waveguide structure include non-linear optical (NLO) polymers.

[0004] In recent years, there has been an increasing interest in synthesizing nanocomposite materials that have applications in the optical communications industry. Nanocomposites containing embedded quantum dots have been recently developed to exploit the extraordinary properties associated with quantum dots. Quantum dots exhibit photoluminescence with high quantum yields.

[0005] There remains a need in the industry for an integrated optical device having components made of nanocomposites or photonic polymers, which can be fabricated by an easily-practiced and low cost process.

SUMMARY OF THE INVENTION

[0006] The present invention provides for the fabrication of an integrated optical device comprising at least one waveguide structure. The waveguide structure is fabricated from a dielectric material selected from either (a) a dielectric matrix having quantum dots dispersed therein or (b) an electro-optical polymer. The fabrication method of the present invention incorporates the technique of nano-imprinting (or nano-embossing) a film of dielectric material to define the shape of the waveguide structure. The integrated optical device of the present invention is operable as one of the following: a wavelength converter, a modulator, a switch, a router, a wavelength filter and a dispersion compensator.

[0007] The advantages and novel features of the present invention will become apparent from the following detailed description of the preferred embodiments of the invention when considered in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] FIG. 1 illustrates a quantum dot that is useful in the present invention.

[0009] FIGS. 2 – 5 illustrate the basic steps for fabricating an optical device according to an embodiment of the present invention.

[0010] FIG. 6 shows the top plan view of the stamp to be used in nano-imprinting according to the present invention.

[0011] FIG. 7 shows a cross-sectional view of the stamp shown in FIG. 6.

DETAILED DESCRIPTION OF THE INVENTION

[0012] The integrated optical device in accordance with one embodiment of the invention comprises a ring resonator coupled to a straight waveguide structure, wherein both structures are formed from a dielectric matrix containing dispersed quantum dots. This embodiment of the present invention exploits the extraordinary optical and electronic properties of quantum dots. The quantum dots may be made of the following materials: (i) Group II-VI semiconductor materials, including but not limited to ZnS, ZnSe, ZnTe, CdS, CdSe, and CdTe; (ii) lead chalcogenides, including but not limited to PbS, PbSe, and PbTe; or (iii) metals having nonlinear susceptibility when introduced into a dielectric host, for example, gold and silver. A quantum dot may comprise a single-material particle or a core surrounded by a shell. FIG. 1 illustrates a core 1 of a first material surrounded by a shell 2 of a second material. Some examples of the core/shell combination are ZnS core/CdS shell, and Au core/CdS shell. The quantum dots are typically in a size range between about 1-50 nm, preferably below 3 nm. It is especially preferred that the quantum dots being dispersed in the dielectric matrix have uniform diameters of 2 nm.

[0013] The dielectric matrix material that is used to host the quantum dots may be selected from a broad range of polymers that are highly compatible with the

quantum dots and have optical properties. Some examples are poly(methylmethacrylate) (PMMA), polystyrene, polycarbonate, polyimide and polysiloxane. The preferred polymers are non-linear optical (NLO) polymers, including but not limited to polyphenylacetylene, and NafionTM (a nonlinear optical polymer available from DuPont). NLO polymers are especially preferred because of their linear electro-optical effects that are important for electro-optical applications. The quantum dots interact with the functional groups on the non-linear optical polymer matrix in order to enhance the optical properties, such as the χ -3, non-linear optical susceptibility. The higher the χ -3, the more the nano-composite would be suitable to perform optical switching. The quantum dots are chosen from II-VI semiconductors, III-V semiconductors and lead chalcogenides in order to embed the quantum dots into different polymers. The properties are screened using various standard techniques, well-known in the art, such as femto-second laser spectroscopy in order to evaluate the χ -3 parameter.

[0014] FIGS. 2-5 illustrate the main steps of fabricating an integrated optical device having a ring resonator coupled to a straight waveguide in accordance with the preferred embodiment of the present invention. Referring to FIG. 2, a dielectric film 4 comprising quantum dots dispersed therein is formed on a substrate 3, preferably a silicon substrate. The thickness of the dielectric film 4 is

preferably about 50-200 nm. Two techniques may be used for forming the dielectric film 4 having dispersed quantum dots on the substrate. According to the first technique, a liquid monomer for forming the above mentioned polymeric matrix is selected, and quantum dots are mixed with the liquid monomer. This mixture is then spin-coated onto the substrate 3. Heating is carried out to polymerize the monomer and to solidify the mixture into the dielectric film 4. According to the second technique, a selected polymeric matrix material is dissolved in a solvent and the polymer solution is spin-coated onto the substrate. The solvent is removed after spin-coating. Quantum dots are then dispersed into the polymeric matrix material by an ion-exchange process, whereby producing the dielectric film 4. The polymeric matrix is prepared so that it has a high content of quantum dots, preferably 60% or higher.

[0015] Referring to FIG. 3, a stamp 5 is imprinted onto the dielectric film 4 to deform the physical shape of the dielectric film 4. Referring to FIG. 6, the stamp 5 has a ring-shaped trench 7 and a linear trench 8 that replicate the shapes of the ring resonator and the straight waveguide structure to be produced, respectively. FIG. 7 shows a cross-sectional view of the stamp 5 formed by cut line I-I shown in FIG. 6. The stamp 5 may be made of silicon, SiO₂ or a metal, e.g., nickel. During imprinting, both the mold and the coated substrate are heated or just the

coated substrate is heated. The heating temperature during imprinting is above the glass transition temperature (T_g) of the polymeric matrix material selected. For example, if PMMA (T_g of 100°C) is the polymeric matrix material then the heating temperature may be above 150°C, preferably 190°C. The stamp 5 and the dielectric film 4 are pressed together at this heating temperature for about 1-10 minutes, followed by cooling down to below T_g so as to harden the dielectric film. After the dielectric film is hardened, the mold is separated from the dielectric layer resulting in a raised pattern of a ring resonator 7a coupled to a straight waveguide 8a as shown in FIG. 4. It is preferred that a releasing agent is provided on the surface of the stamp in order to improve the resolution of the imprinting and improve the minimal feature size. Etching is then carried out to remove the excess matrix material surrounding the raised structures 7a and 8a, thereby exposing the top surface of the substrate 3 as shown in FIG. 5. The etching step may be done by wet etching using buffered HF. Etching also increases the aspect ratio of the side wall surfaces of raised structures 7a and 8a.

[0016] In the second embodiment of the present invention, the dielectric film to be imprinted is made of an electro-optic polymer. The preferred electro-optic polymer is one which has a highly polymerizable chromophore in its back bone or side chain. As an example, electro-optic polymers available from Pacific

Wave Industries, Inc., CA (US) are suitable for the purpose of the present invention. The electro-optic polymer in the form of a solvent-based solution is coated onto a substrate, preferably by spin-coating. The solvent is then evaporated from the polymeric coating to form a solidified polymer film. The same imprinting, cooling and etching steps are then carried out as described above for FIGS. 3-5 to produce a ring resonator coupled to a straight waveguide structure.

[0017] It should be understood that two or more ring resonators in combination with two or more straight waveguide structures may be produced by the method of the present invention.

[0018] The invented method of fabricating the basic device having a ring resonator coupled to a straight waveguide may be incorporated in the fabrication of one of the following optical devices: a wavelength converter, a modulator, a switch, a router, a wavelength filter and a dispersion compensator.

[0019] There are two kinds of nanoimprinting techniques: (1) hot embossing and (2) cold embossing involving ultraviolet lithography. Either technique may be

used in the method of the present invention. The principal process steps for an UV-NIL process are:

- (1) Loading of stamp and spin coated substrate;
- (2) Adjusting of a certain separation gap between stamp and substrate;
- (3) Rough alignment of stamp and substrate in adjusted separation;
- (4) Moving to soft contact of stamp and resist;
- (5) Fine alignment of stamp and polymer in soft contact;
- (6) Vacuum contact between stamp and resist;
- (7) Curing of imprinted features by UV-exposure;
- (8) Demolding of stamp and imprinted substrate;
- (9) Unloading of imprinted substrate;
- (10) Loading of next substrate; and
- (11) Returning to step (2).

[0020] The present invention has numerous advantages over existing developments, including:

[0021] (a) The inventive method can produce waveguide structures with small feature sizes of sub-50 nm resolution.

[0022] (b) The present invention provides a high-throughput, easily practiced and low cost fabrication method that eliminates multi-stage etching procedures.

[0023] (c) The polymer waveguides with very smooth sidewalls can be fabricated, thereby producing very little scattering loss.

[0024] (d) Tunable micro-ring structures can be fabricated for resonator or modulator applications. During the fabrication of the micro-rings, the exact size can be easily controlled.

[0025] Although certain preferred embodiments have been shown and described, it should be understood to those skilled in the art that many changes and modifications may be made therein without departing from the spirit and scope of the invention as defined by the appended claims.